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Review

Environmental Sustainability of Plastic in Agriculture

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Abstract: This article investigates the environmental sustainability of plastic nets in agricultural environments based on published experimental data. This article focuses on biodegradable and synthetic plastics used in farms as mulching materials and shade materials/greenhouse covering materials (shade nets and plastic films) to protect plants from pests and extreme weather. The sustainability was determined by three factors, carbon footprint from cradle to the end of life (LCA), durability (resistance to photo-oxidation and high tensile strength), and affordability. The LCA analyses showed that the production of polyethylene (PE) requires less energy and generates low quantities of greenhouse gas equivalents. Beyond the LCA data, biodegradable polymers are sustainable based on biodegradability and compostability, ability to suppress weeds, control soil temperatures, and moisture, and augment fertigation and drip irrigation. However, existing technologies are a limiting factor because lab-based innovations have not been commercialized. In addition, industrial production of shade nets, plastic greenhouse covers, and mulching materials are limited to synthetic plastics. The bio-based plastic materials are sustainable based on biodegradability, and resistant to photo-oxidation. The resistance to UV degradation is an essential property because solar radiation cleaves C-C bonds, which in turn impact the mechanical strength of the materials. In brief, the sustainability of plastics in farms is influenced by LCA data, mechanical and optical properties, and performance relative to other materials.

Keywords: polymer; recycle; sustainability; PE; PLA/PHT; greenhouse cover materials; plastic nets

1. Introduction

The publication reviews the environmental sustainability of plastics in agriculture, especially in the commercial production of fruits, vegetables, and cereals within the EU and the US. The investigation focuses on both biodegradable (such as polylactic acid, PHA) and non-biodegradable linear low-density polyethylene (LLDPE), polyvinyl chloride, and polypropylene (PP) and polyethylene (PET) plastic shade nets (wind-break nets, shade, anti-insect, and anti-hail plastic nets), plastic covers, and mulching films. The materials were selected because they account for nearly all plastics used in farms. Previous studies show that the sustainability of plastic nets is dependent on the precursors used in plastic production [1,2] and the utilization of biodegradable materials such as poly-lactic acid (PLA) in place of PP and PET [3]. The main hypothesis is that the ecological impact (quantified by LCA) of biodegradable plastics is influenced by the chemical composition of the plastics.

Plastic shade nets are essential in farm environments because they enhance agricultural yields and nutritional properties, limit insect infestation, exposure to solar radiation, and meteorological events such as hail and storms [4–7]. The plastic nets alter the microclimate and limit the impact of natural elements on plants. On the downside, the plastic exclusion nets compromise natural biodiversity, including spider communities [8]. The cost-benefits favor the utilization of plastic nets on the farm. However, delayed and early production models have negative environmental impacts. However, the adverse ecological impacts were offset by the economic benefits in terms of the value of the harvest [9].

The sustainability of the plastic nets was considered from the perspective of life cycle assessment (ecological impact of these materials/carbon footprint in the production phase), useful life in the farm environment (durability based on mechanical properties) and recycling/degradation of the plastics in the farm environment [10]. The outcomes drawn from the review would help establish whether the adoption of biodegradable plastics in agricultural production was practical considering the production-related limitations, affordability of non-biodegradable polymers, and limited consumer acceptance of green plastics.

Beyond plastic nets, plastic mulching films and plastic covers for greenhouses are common in small scale and large-scale agriculture. Zhang et al. (2019) [11] estimates that about 40,000 km^2 of European farmlands are covered by plastic films; this demonstrates the centrality of plastic shading technology in modern agriculture. A similar demand has been observed in plastic mulching materials, which help to regulate soil moisture content, temperature, and limit the growth of weeds [6]. However, agricultural plastics mainly comprise of synthetic materials because the global supply of bio-based plastics has remained low (~1.7 million tons) [10]. Even though supply does not match the demand, the focus on biodegradable plastics in agricultural applications is premised on ecological and sustainability considerations. For example, biological and abiotic degradative processes which trigger degradation [12]. On the downside, there are multiple concerns about the impact of synthetic plastic mulching on soil water repellency, soil degradation, enhanced pesticide runoff, accumulation of plastic residues and formation of micro-plastics, and biogeochemical processes [13].

Non-biodegradable plastics are sourced from fossil fuels, and the production process generates significant quantities of CO_2 into the atmosphere, which is a primary concern considering the rate of global warming and climate change. In contrast, bio-based plastics derived from renewable feedstocks pose a minimal threat to the environment [14]. The latter materials have been developed from a wide array of sources including corn starch [15], rice husk [16], pectin [17], and food waste [18]. Beyond the low carbon footprint and environmental burden, bio-based and biodegradable polymers are suitable because the surface properties can be customized to poses anti-bacteria/anti-microbial properties [19,20]. Additionally, the mechanical, radiometric, thermal, and optical properties of the material are tunable [21–23]. The literature review section focuses on the modification of the mechanical, optical, and radiometric properties.

2. Review of Plastic Nets and Covers

Previous research studies relating to the environmental sustainability of plastics in agricultural applications focused on two main uses (mulching and shading), as noted in the introduction. The utility and ecological sustainability of farming applications were influenced by the adjustment of the mechanical, optical, radiometric, and related properties. The effects of modifying material properties are reviewed in the next section.

2.1. Modification of Mechanical Properties of Shade Nets and Environmental Sustainability

The review of the mechanical properties of shade nets is critical to sustainability because of the following facts. One, the mechanical properties predict the useful life in the farm; exposure to extreme environmental conditions such as storms, rainfall, and prolonged sunlight and chemicals in pesticides impacts durability. For example, UV light degrades plastic materials. Therefore, the modification of the material properties to improve durability may contribute to sustainability considering the carbon footprint and ecological impact of synthetic plastics on the environment. The environmental impact is considered in Section 2.6 (Life Cycle Analysis). In the present subsection, various methods used in the reinforcement of the mechanical properties of shade nets, including the addition of fibers to form fiber-reinforced polymers, blending, and the inclusion of biomaterials such as chitosan are discussed.

According to an experiment conducted by Black-Solis et al. [24] the mechanical properties of agricultural nets can be reinforced by blending poly (butylene adipate-co-terephthalate) (PBAT), poly (butyl acrylate) (PBA), poly (butylene succinate-co-adipate) (PBSA), and polycaprolactone (PCL).

The blended product had better mechanical and physical properties such as elongation and flexibility at break compared to the constituent materials. The phenomenon could be attributed to the unique features of the constituents, especially PBAT. The material exhibits optimal performance over a wide pH range. Additionally, it is ductile and compatible with other biodegradable polymers. Even though the blending of different types of biodegradable polymers was proven effective by Black-Solis et al. [24], a criterion should be adopted in the selection of the constituent polymers to preserve the fundamental material properties and ensure that the materials were compatible. The unique features of other potential polymer blends, such as the tensile strength, elongation at break, glass transition temperature, and the melting points for different biodegradable materials, are presented in Table 1.

Chitosan is an ideal additive material for enhancing the sustainability of plastics in farm environments because it forms extensive cross-linkages, substantial intra, and intermolecular hydrogen bonds, and has a compact crystalline structure [25]. Additionally, the material has anti-microbial properties and can easily be extracted from crustaceans and insects [26]. On the downside, the scope of application of chitosan is limited by solubility in different solvents. However, the limitations are not an impediment to the utilization of the material considering that biocompatibility, non-toxicity, and anti-microbial properties outweigh the limited solubility, which can be partly offset by modifying the chemical properties of the chitosan. Bashir and co-researchers noted that biodegradable plastics made from polyvinyl chloride, chitosan, mint, and grape seed extract materials had ultimate tensile strength values between 15 and 28 MPa and an elongation at break of 86% [27].

Table 1. Mechanical properties of selected biodegradable polymer materials [28].

Property	Type of Biopolymer						
	PLA	**l-PLA**	**dl-PLA**	**PGA**	**PCL**	**PHB**	**Starch**
Density (kg/m^3)	1210	1240	1250	1500	1110	1180	-
Tensile strength (MPa)	21	15.5	27.6	60	20.7	40	5.0
Young's Modulus (GPa)	0.35	2.7	1	6	0.21	3.5	0.125
Elongation (%)	2.5	3	2	1.5	300	5	31
Glass transition temperature (°C)	45	55	50	35	−60	5	-
Melting temperature (°C)	150	170	am	220	58	168	-

Commercially available blends of chitosan containing polymers include Chitosan-Starch-Pectin, high methoxyl pectin (HMP), and low methoxyl pectin (LMP) have been developed for packaging agricultural produce [14]. In brief, the utility of chitosan in enhancing the mechanical properties of bio-based polymers has been widely proven. Apart from improving the mechanical properties, chitosan is ideal for surface modification to enhance the pest-inhibition ability of shade nets and packaging films [1].

Bamboo fibers have also been proven to be suitable alternatives for reinforcing the mechanical properties of polymers. The superior mechanical strength of the bamboo fiber reinforced polymers is derived from lignin, cellulose, and hemicellulose [26]. On the downside, the material has been adopted in limited polymer applications compared to the manufacturing of composites. Beyond the addition of fibers, the strength of the polymers is augmented by modifying the manufacturing conditions and post-production pre-treatment.

Even though there are multiple practical methods for enhancing the mechanical properties of shade nets and other types of plastics used in farm environments, the researcher is cognizant of the fact that the enhancement of the tensile strength often involves a tradeoff with ductility, which in turn elevates the risks associated with brittleness. Another issue of concern is the potential costs associated with the modification of the mechanical properties and the life cycle analysis; there is limited data to establish if available methods were cost-effective and scalable and environmentally benign. Based on the gaps in the available body of knowledge, upcoming studies should focus on these issues.

The significant variations in the weather patterns should be taken into consideration in the production of shade nets and mulching films; this is because they influence exposure to hail, frost [29], severe storms, and excess solar radiation. A high level of solar radiation exposure is capable of inducing photodegradation/light-induced damage to plastic materials [30]. Even though the risks associated with photodegradation can be mitigated by the inclusion of photo stabilizers and antioxidants [31], UV damage of plastic shade nets and mulching materials is a common problem in tropical areas. Such areas receive intense sunlight compared to the subtropical/temperate zones. Additionally, the duration of global solar radiation exposure is longer, as shown in the appendix section.

The observation is supported by experiments conducted in the arid areas of Saudi Arabia [27]. Arid and desert regions have sand storms, with pronounced tensile and shear stresses, which degrade the mechanical properties of the material. Based on the geography-specific challenges reported by Abdel-ghany et al. [30] and Briassoulis et al. [32], the weather patterns influence the sustainability of the material in agricultural applications. Apart from UV degradation, the starch content in the biodegradable polymers predicts the rate of natural deterioration. Luckachan and Pillai [33] reported a 30% weight reduction after 8 months of exposure to Baltic Seawater. On the downside, such risks are not adequately taken into consideration during the selection of greenhouse materials.

2.2. Modification of Optical Properties of Shade Nets and Environmental Sustainability

Similar to the modification of the mechanical properties, optical properties have an impact on environmental sustainability because they determine a plant's IR absorbance and transmittance, heat transfer, UV and radiation control [2]. The regulation of these variables determines agricultural yields and plant health. Poor/low yields have a domino effect on sustainability considering that commercial agriculture contributes to global warming [34]. From a practical point of view, it is hypothesized that poor yields would require intensification of farming (increasing the acreage under cultivation) to meet market demands.

The optical properties of different shade net materials were modified by adjusting the intensity of the shade nets and the surface color. According to the data presented in Table 2, shade nets with green and black strips had a shading intensity of 34% and 40%, respectively. Even though the variations in the shading intensity were non-significant, they impacted the transmission of photo-synthetically active radiation (PAR), light transmission in the near-infrared, and the total transmission band. The transmission of light beyond the acceptable values impacted fruit/vegetable yields and exposure to pest and disease and physiological disorders such as cat face, skin cracking, sun scalding, and blossom end rot. Following the review of the material properties, the selection of the most suitable material does not involve a tradeoff between the optical properties, and the marketable properties of the fruits.

Table 2. Impact of plastic shade netting on optical properties [34].

Transmission Coefficient	**Screen House Material**				
	Control				
	(No Screen)	**Gr34**	**B&Gr40**	**B40**	**B49**
PAR	–	63.4	57.4	60.7	51.3
NIR	–	71.2	60.7	60.5	53.4
TMB	–	65.6	58.8	60.6	52.2
b	1.26	1.16	1.20	1.26	1.25
n	1.30	1.22	1.26	1.28	1.27
B: R	1.04	1.13	1.04	1.02	1.04
B: FR	1.32	1.30	1.25	1.28	1.29
PAR: TMB	0.58	0.56	0.57	0.58	0.58
PAR: NIR	1.39	1.23	1.31	1.39	1.35

B49 (black shade net with a shading intensity of 49%) had the lowest PAR transmission rate, and highest marketable yield, mean fruit mass, and physiological conditions [34]. The combination of the optical properties and reduction in plant's exposure to pest and diseases makes material number B49 most ideal compared to Gr34 (green with a shading intensity of 34%) and B&Gr40 (black and green with a shading intensity of 40%) [34]. The impact of shade net colors on optical properties reported by Kittas et al. [34] is consistent with findings published by Milenkovi [35], who reported optimal tomato fruit yield in red and pearl shade nets with 40% shade. The variations in the performance of the shade nets illustrate that there was no standard net color or shading intensity, which is appropriate. The color suitability is influenced by the type of plant under the shade net conditions and the local weather patterns and the grade of shade nets.

2.3. Plastic Covers/Films for Greenhouses

Plastic covers for greenhouses complement shade nets, especially when creating a local micro-climate is necessary to protect plants from the external environment. Plastic films also prove effective in solarization, better heating efficiency, and facilitate soil nitration [36,37]. However, soil solarization involves a tradeoff between the destruction of pests and disease and the reduction in the richness of bacteria and fungi, which is beneficial to plant growth [38]. Additionally, there are sustainability concerns relating to the utilization of synthetic films in solarization and the limited efficiency of biodegradable plastics [39]. According to [32], the plastic covers provided an insect-proof screen, which in turn, eliminated or reduced the frequency of pesticide applications. The surface properties of the plastic covers can be modified to slowly release pesticides, as noted by [33]. The slow release of pesticides is an effective form of integrated pest management (IPM) because constant flow of pesticides limits the proliferation of pesticides and reduces waste and soil toxicity. From an environmental point of view there are also contraindications: resistance to insecticides and diseases, contamination during installation, release of toxic substances into the environment. The use of substances compatible with organic agriculture would be perfect.

Apart from covering greenhouses, the films are ideal mulching materials compared to organic matter such as hay/dried grass. Zhang et al. [11] argue that plastic films are suitable because they suppress weeds, facilitate fertigation and drip irrigation, regulation of soil temperatures, regulation of soil temperatures, and converse moisture. The observations are in line with Briassoulis and Giannoulis's [10] assessment of the functionality of bio-based polymers in mulching applications. However, the tensile strength of the commercially available bio-based films (Ecovio and Mater-Bi) was lower relative to the control (LLDPE) in both the transverse and machine directions, as shown in Figure 1 [10]. The tensile strength is a critical factor in predicting aging and failure. The failure of bio-based polymers results in the perforation of the film by weeds and free-falling objects. The susceptibility to mechanical damage limits the durability of the bio-based films.

The main challenge is to achieve similar capabilities using bio-based polymer films/covers. The data reported by Antón, Torrellas, Raya, and Montero [39] and Seven, Tastan, Tas, Ünal, and Ince [40] is based on polycarbonate and LLDPE films, which are not biodegradable. However, the degradation process can be augmented by UV light and oxidizing agents [41]. Alternatively, the chemical structure can be modified to integrate carbonyl groups in PE, which are easily cleaved by microorganisms [41]. The insights drawn from anti-microbial methyl-cellulose, organoclay, and coffee grounds based packaging films [34] could help reduce the environmental effects of polycarbonate and LLDPE films in commercial farming. New materials with the potential to kill weeds have been developed such as de-oiled pomace (DOP) and their application has been proven in oil orchards [42]. In addition, biodegradable sprays and drip irrigation systems have been investigated in the cultivation of ornamental shrubs and greenhouse plants [43,44]. The mulching sprays were effective in preventing the growth of *S. asper* but less effective for *E. montanum*.

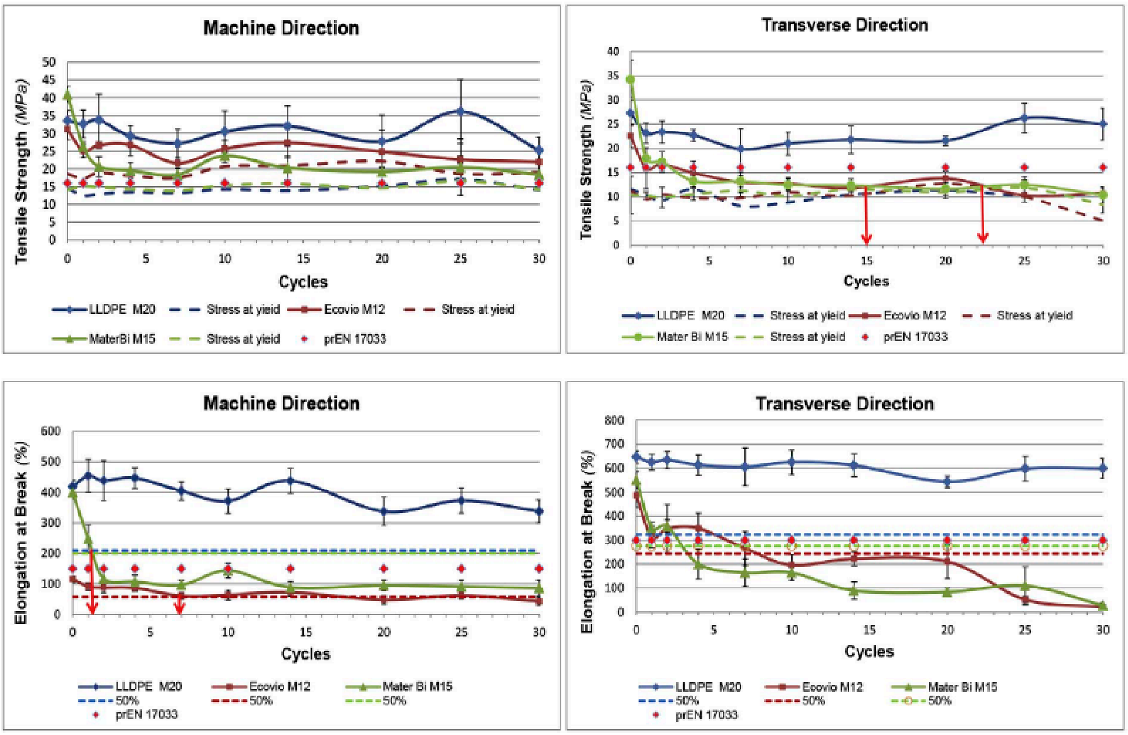

Figure 1. Tensile strength of bio-based polymers versus synthetic plastic films and cycles to failure [10].

Recent LCA analyses show that synthetic plastic films pollute the environment during the end of life treatment (landfilling, incineration, and recycling) [45]. The long-term effects on the environment offset the superior material properties of the synthetic plastics.

Considering that bio-based plastic films offer near similar performance as synthetic plastics in reducing weeds, control of soil temperatures and moisture, and augment drip irrigation and facilitate fertigation, the main question is whether carbon footprint considerations should be a priority compared to durability and cost. The bio-based polymers are less affordable due to limited supply and commercial adoption. The selection of the materials should be based on context-specific factors such as the plant growth cycles, weather, and farming practices (such as organic farming). The economics of bio-based films are reviewed in the next section.

Potato Starch

The performance of plastics has also been augmented by the inclusion of organic materials. For example, potato starch blended with poly(hydroxybutyrate) (PHB) can be used to enhance the thermal stability and glass transition temperature of the biopolymers [28]. The materials formed using these methods exhibit a glassy thermoplastic behavior that is comparable to HDPE and PP. Additionally, the potato peel waste is an ideal raw material for bio-composites and biopolymers [46]. The materials can be used in the development of bio-based plastics for greenhouses and mulching films, and potato starch-graft-poly (acrylonitrile), chemical grafting is an ideal method for modifying the chemical properties of biopolymers [47].

2.4. Modification of Plastic Covers/Films

Similar to the plastic nets, the mechanical and optical properties of plastic covers and films can be modified to reduce the impact of UV damage and photo oxidation and improve durability in farm application. Various methods have been adopted in the modification of the plastic net properties including optimizing the permeability, thickness, aspect ratio, and mass [48,49]. Additionally, surface color and surface modification (water-filled bubbles on the surface) have been explored (Figure 2).

The findings reported by Oz and co-researchers showed that surface modification of the plastic covers and films facilitated the regulation of soil temperatures and soil nitrogen, which in turn, had an impact on plant growth.

Figure 2. Surface modification of mulching PE materials [38].

2.5. Degradation and Compostability

Apart from the modification of the microstructural properties to achieve better mechanical properties, optical reflectance, and customizable transmission of UV radiation (optical and radiometric properties), the rate of natural degradation and compostability predicts the environmental sustainability of plastics in agricultural settings. Synthetic plastics such as HDPE, PET, and PP plastics are not biodegradable; this is demonstrated by the low specific surface degradation rate (SSDR) of 10^2 and 10^3 μm/year [50]. The limited biodegradability of these structures is attributed to the unique chemical properties and bonding. The synthetic plastics have strong C-C bonds, which are resistant to photo-oxidative degradation. Additionally, the bonds are not easily hydrolyzed. However, the challenge can be offset by modifying the structure to include functional groups with C=C, and C=O bonds indirectly facilitate photo-oxidation because the functional groups are capable of absorbing UV radiation. Considering that the SSDR is lowest on land, landfilling waste plastics (shade nets and mulching materials) is not a practical option because there is a risk of micro-plastic and plastic debris accumulation [51]. Additionally, incineration or recycling is limited by cost considerations because the procedure generates significant volumes of waste. The degradation of plastics in farms can be induced by microbial activity (enzymatic activity and microbial metabolism) [39] since landfilling is not a viable ecological approach.

Bacterial activity is primarily confined to bio-based plastics, which contain organic materials that can be converted to water and carbon dioxide. However, the effectiveness of this method is also dependent on the prevailing meteorological conditions (primarily the intensity of solar radiation, relative humidity) and geography. Rudnik and Briassoulis [52] noted that the hydrolyzation of the plastic materials was enhanced in high humidity environments. Additionally, optimal microbial action was observed in warm/hot weather.

Even though biodegradable plastics are susceptible to environmental degradation, the phenomenon is not ubiquitous, especially given that the polymers are blended with standard non-biodegradable materials and additive to enhance the desired properties [39]. The decline in the rate of biodegradability is correlated with the ratios of the biopolymer blends. A higher proportion of biopolymer blends translates to better standards of biodegradation. However, the ecological effects associated with blending can be offset with the recent advances in material development. For example, Black-Solis et al. [24] noted that the physical properties of PLA biopolymers could be enhanced by blending with novel biodegradable materials including poly (butylene adipate-co-terephthalate) (PBAT) and poly (butylene succinate-co-adipate) (PBSA) to improve the physical properties of the polymers. The latter approach eliminates the need for non-biodegradable polymer blends. On the downside, there is minimal evidence of the commercialization of these innovations.

Commercially available shade nets and mulching materials are blended with non-biodegradable materials—a process that involves a tradeoff between environmental pollution and better mechanical strength [53]. The compostability of plastics in farms is distinct from biodegradability. The process of compostability is defined by fragmentation in the environment, the rate of conversion to CO_2 and biomass, the presence of metals and other impurities, and the ability to support plant growth [54]. Following the review of these parameters, compostable plastics exhibit unique behaviors in the environment compared to biodegradable plastics. On the downside, nearly all plastics used in agricultural applications are not compostable, except for twines and clips used to support greenhouse plants. The environmental benefits associated with compostability versus biodegradability can be contested based on the following facts. First, compositing bio-based plastics is time-intensive and requires elevated temperatures (58 °C). Additionally, moisture and airflow should be optimized. The complexity of such procedures limits the compositing of plastics in farm environments. From an ecological point of view, the biodegradability of plastics is a fundamental criterion compared to compositing.

2.6. Life Cycle Analysis

The LCA-analysis of bio-based and synthetic plastic outlines the carbon footprint, energy demand, and other adverse ecological effects from the cradle to the grave. The environmental impact of the production process is reviewed.

2.6.1. Production of Synthetic and Biodegradable Polymers

The production of HDPE plastics is associated with a 52% global warming potential of the entire production process [55]. Additionally, a comparative analysis of biodegradable (PLA) and non-biodegradable polymer (PE) in Table 3 shows that the synthetic process of the latter poses a minimal threat to the environment. In particular, the energy demand for PLA4 is 24 MJ/kg; this contrasts with 76 MJ/kg for PE. The data shows that the production of synthetic plastics requires threefold higher energy. The GHG emissions kg CO_2 equivalent/kg is higher for PE compared to PLA (4.8 vs. 1.8) [56]. The estimates are consistent with the global forecast, which showed that the production of synthetic plastics generated 1.7 Gt of CO_2-equivalent [57]. Since agricultural plastics account for 2% of the global demand [58], 340 megatons of CO_2-equivalent were generated from agricultural-related applications; this is an issue of environmental concern because carbon emissions are projected to increase fourfold by 2050 [57]. The ecological risks could be mitigated by the commercialization and production of bio-based plastics with suitable mechanical, optical, and radiometric properties.

Table 3. LCA analysis for PLA and PE (energy and greenhouse gasses (GHG) emissions kg CO_2 eq) [56].

Material	Energy	Weight	Energy	GHG Emissions	GHG Emissions
	MJ/kg	kg/FU	MJ/FU	kg CO_2 eq/kg	kg CO_2 eq/FU
PE	76	0.2	15.20	4.80	0.96
oxo-PE	-	0.2	15.20	4.80	0.94
PE	76	0.196	14.90	4.80	0.94
Fe	68	0.00132	0.09	-	-
Mn	52.78	0.00132	0.07	-	-
Co	109.1	0.00132	0.14	-	-
PLA1	54	0.3	16.20	4.00	1.20
PLA2	40	0.3	12	3	0.90
PLA3	29	0.3	8.7	1.89	0.57
PLA4	26	0.3	7.8	1.80	0.54

The data provided by Grigale, Simanovska, Kalnins, Dzene, and Tupureina [56] and Mukherjee, Knoch, and Tavares [55] cannot be generalized to other plastics; this is because the LCA cycles of PLA and PE do not represent other biodegradable and fossil fuel-based polymers. The production process of synthetic polymers is customized to attain the desired physical, chemical, and molding properties. High pressure and low-pressure polymerization yield HDPE and LDPE plastics [59]. Additionally, the energy demand varies in high and low-pressure polymerization processes. In addition to the type of plastic produced, the ecological effects are influenced by the kind of raw material—recycled or virgin materials [47].

The LCA data demonstrates that the production of synthetic polymers is carbon and energy intensive. The LCA estimates for PLA reported by Grigale et al. [56] are not in line with Pikoń and Czop [60], who noted that the environmental impact of PLA was comparable to non-biodegradable plastics. The poor ecological rating of biodegradable plastics was associated with higher energy expenditure, transport costs, and a slow rate of biodegradation. Even though the LCA analysis for PLA was unsatisfactory in the latter case, PLA and other biopolymers have a lower ecological burden over the long-term considering that fossil fuel precursors are not issues. The carbon footprint can be mitigated by replacing the plastic materials with biopolymers or blending. The findings presented in Table 3 validate the main research hypothesis listed in the introduction because the chemical composition of the plastics predicted the carbon footprint, energy expenditure, and other critical LCA variables. For example, PE-based plastics had a higher carbon footprint compared to PLA, which has characteristic C=O bonds/functional groups. The main exception is PLA1. The LCA shows that the carbon footprint of synthetic polymers limits the sustainability of the materials. The ecological impact of the materials during recycling, landfilling, and disposal is presented in the next section.

2.6.2. Useful Life and Disposal

The disposition and useful life phases of biodegradable polymers and synthetic polymers have a secondary impact on sustainability, considering that at least 131–627 kg/ha of shade net waste is generated each year in the farm [58]. Mechanical recycling, industrial composting, and chemical recycling are viable disposal method for agricultural plastics, considering that landfilling in farms is not a practical alternative. However, the recycling process has mixed benefits. On the one hand, it facilitates the removal of excess plastics from the environment. On the other hand, the process generates secondary pollutants, and the process is not 100% effective [3]. The sustainability of existing recycling methods is impacted by the low-quality of the recycled materials, reprocessing cycles, and high energy demand during chemical recycling/pyrolysis [61]. In brief, technological limitations limit the effectiveness of mechanical and chemical recycling.

2.7. Spread of Micro-Plastics in the Environment

Micro-plastics are small plastic fragments with a size that varies between 0.5 and 5 mm [50], which originate from plastic additives and plastic debris [61]. In 2020, there were at least, 250,000 tons and 51 trillion pieces of micro-plastics [61]. Additionally, the micro-plastics are the most common forms of plastic pollutants in oceans—94.6% of plastics in the Mediterranean Ocean were micro-plastics in 2019 [62]. The spread of micro-plastics within the environment is a limiting factor in the utilization of plastic materials in farm environments. For example, micro-plastics pollute the marine environment [63]. However, the exact mechanism through which the plastics impact marine and freshwater ecosystems largely remains unknown. One school of thought suggests that isotropic motion (a defining attribute of micro-plastics) coupled with low aspect ratios result in unique fragmentation behavior in the oceans. The unique fragmentation behaviors also limit the formation of biofilms, and by extension the probability of decomposition. In contrast to biofilms, which are degraded naturally in the environment, micro-plastics exhibit oxygen incorporation, which translates to an increase in the mass and the attraction of micro-organisms [50], which may latter aid the degradation process. However, since the degradation process is slow the risk of ingestion by marine species remains high [62]; this would impact human health considering that seafood is a staple diet in coastal areas.

2.8. Plastics for Packaging Versus Plastics for Farm Applications

Plastic materials used for packaging applications have unique properties compared to those used in farms. For example, plastic films have microbial agents to inhibit microbial growth in plants [20]. In contrast, plastics used in farms have unique properties that are used to enhance the mechanical behavior of the plastics and suitability in farm environments such as the ability to slowly release insecticides [41], moisture retention and mitigation of weeds [10]. Even though, the two types of plastics serve different functions. Post-consumer usage and handling of these plastics pose a threat to the environment. On the one handling, landfilling and partial recycling of plastics is common for synthetic plastics. On the other hand, the degradation of bio-based plastics results in the generation of micro-plastics, which are transferred to waterways and absorbed by marine species [64]. Alternatively, the micro-plastics are wind dispersed to other geographical areas resulting in land pollution.

Production Strategy of Farms (Seasonal, Early, Postponed Production) and Environmental Analysis

The agricultural production strategy adopted in farms has a profound impact on the utilization of plastic nets, greenhouse covering, and mulching materials. First, seasonal crops require plastic shading materials to optimize growth even though the cultivation process is dependent on the weather patterns. For example, the quality of sweet pepper plants grown under greenhouses was better compared to controls cultivated outside greenhouses [65]. The improvement in plant quality was due to the mitigation of the transmission of Tomato yellow leaf curl virus, Tomato yellow leaf curl Sardinia virus, and Tomato chlorosis virus, which is transmitted by whitefly [65]. Beyond the mitigation of insect transmission of diseases, plastic net colors had an impact on fruit quality [66]. Considering that fruit and plant quality was dependent on plastic materials, postponement of production had an impact on the environment because the durability of plastic covering materials for greenhouses is limited. The durability is compromised by poor mechanical strength, periodical exposure to UV radiation in the absence of stabilizers [67], and exposure to meteorological conditions.

2.9. Plastics for Soil Solarization and Degradable Sprays Used as Mulch

Soil solarization is a technique that is employed in mitigating insects which are sensitive to temperature [36]. The process involves wrapping the soil with PE films for 60 days (2 months) during the hottest season. High soil heating prevents dehydration and the flow of UV radiation leading to the death of the insects [36]. From an ecological point of view, the method is better compared to the utilization of degradable sprays. The claim is based on the fact that less than 1% of sprays reach the target sites, the rest spreads on the soil [41]. The waste is non-beneficial to the environment.

2.10. An Economic Study of the Costs of Synthetic Versus Biodegradable Plastics

The economic costs of biodegradable plastics are depicted in Tables 4–6. The data shows that the production of PLA from waste would yield a return of investment (ROI) of about 56% per year [68]. The outcomes show that the production of bio-based polymers is economically viable. However, the significant initial capital outlay ($31 million) required for the project was an impediment to the commercialization process. Additionally, the estimates are based on the production of both PLA pellets and filaments.

Table 4. Initial investment costs [68].

Item	Number of Units	Cost Per Unit in L.E.	Item Cost in L.E.
Land (4000 m^2)	-	-	11,000,000
Building (2000 m^2)	-	-	20,000,000
Waste Conveyer Belt	2	85,000	170,000
Forklifts	4	25,000	100,000
Pellets Rack	100	1800	180,000
Chemical Storage Cabinet	10	5100	51,000
Packaging Machines	2	50,000	100,000
Glassware	NA	100,000	100,000
Total	-	-	31,701,000

Table 5. Investment costs [68].

Item	Number of Units	Cost Per Unit in L.E.	Item Cost in L.E.
Magnetic Stirrer	1	100,000	100,000
Shaker	5	2000	10,000
Spectroscope	2	100,000	200,000
Refrigerator	4	20,000	80,000
pH Meter	2	20,000	40,000
Fermenter	4	200,000	800,000
Autoclave	4	20,000	80,000
Centrifuge	4	50,000	200,000
Incubator	10	35,000	350,000
Evaporator	2	50,000	100,000
HPLC Apparatus	2	300,000	600,000
Computer	4	25,000	100,000
Deionized Water Apparatus	1	35,000	35,000
Total	-	-	2,695,000

Table 6. Expected returns on investments [68].

Item	Quantity	Revenue	Cost	Profit	ROI Yearly
PLA Pellets	176	1,267,200	944,370.24	322,829.76	10.8%
PLA Filaments	44	1,584,000	231,692.56	1,352,307.44	45.6%
Total	220	2,851,200	1,176,062.8	1,675,137.2	56.4%

2.11. Limitations

The main limitation of this research is the focus on published data in place of empirical observations. From an agricultural point of view, the present review may not reflect the current state of events because novel and next generation plastic materials such as polydiketoenamine [69] have been developed in the recent past, the efficiency of such materials in agriculture has not been documented in literature. Additionally, the scope of the review is limited to mulching film, plastic nets, and films for greenhouses, even though there are other forms of plastic materials.

3. Conclusions

The paper builds upon published experimental data specific to the environmental sustainability of nets in agricultural applications. The sustainability of plastic shade nets, and mulching materials was based on the following criteria: mechanical properties, optical and radiometric properties, LCA analyses, biodegradability, and compostability. The mechanical and optical properties helped to predict the durability of the plastics in farm environments while the biodegradation rates and LCA predicted the impact on the environment.

A review of bio-based polymers and polymers manufactured using renewable feedstock and synthetic plastics derived from fossil fuels confirmed that the latter materials posed a more significant threat to the environment because the specific surface degradation rate (SSDR) was below the threshold. Additionally, landfilling and incinerating the waste were not practical alternatives. Additional constraints include the carbon-intensive production process. Despite these disadvantages, synthetic plastics such as LDPE, HDPE, PP, and PET are affordable, and existing production methods are compared to bio-based polymers. Additionally, the materials are resistant to UV photodegradation, which is a critical constraint in tropical areas/arid regions, which receive intense solar radiation.

A comparison of bio-based and synthetic plastics shows that the two materials offer similar benefits in preserving soil moisture, regulating local soil temperatures, enabling drip irrigation and fertigation, and eliminating weeds. However, there are other unique benefits associated with each material. On the one hand, bio-based polymers have a low carbon footprint from cradle to the end of life treatment. On the other hand, synthetic plastics are durable and affordable.

Price consciousness among consumers has contributed to better consumer acceptance of fossil fuel-based plastics. However, consumer attitudes could be reversed with the development of 100% degradable plastics, which are devoid of synthetic polymer blends. On the downside, there is limited data concerning shade nets and mulching materials made of PLA/PHA blended with poly (butylene succinate-co-adipate) (PBSA) and polycaprolactone (PCL), poly (butylene adipate-co-terephthalate) (PBAT), poly (butyl acrylate) (PBA). In brief, the impact of biodegradability on tensile strength, optical and radiometric properties is not adequately defined. However, there is definitive evidence that biodegradability of PLA and other bio-based plastics has long term ecological benefits.

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Abbreviations

GHG	Greenhouse gas
HMP	High methoxyl pectin
LCA	Life cycle analysis
LLDPE	Linear low-density polyethylene
LMP	Low methoxyl pectin
PAR	Photosynthetically active radiation
PBA	Poly (butyl acrylate)
PBAT	Poly (butylene adipate-co-terephthalate)
PBSA	Poly (butylene succinate-co-adipate)
PCL	Polycaprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Poly-lactic acid

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